

# **Model-based Breed and Burn Reactor**

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## **Abstract**

Presently, hundreds of temporary storages hold spent fuel at densities that approach those in reactor cores, creating a high potential for radioactive leakage and terrorist attack. Depleted uranium dioxide, which is an excellent semiconductor and could be a major resource of energy, is now being managed as waste. A process, pioneered by WETC, could convert depleted uranium or thorium into high energy density fuel. The process, involving a proliferation-resistant fuel cycle without uranium enrichment and plutonium isolation, would avoid keeping the gaseous fission fragments restrained in the fuel elements, an innovative strategy used to monitor and control a LWR-type breed-burn reactor. In-core monitoring systems that included some aspects of this design were tested in the mid 1980s and demonstrated that uses of electrical properties of actinides could lead to essential improvement of reactor performance.

Thus, the deposition techniques widely employed in semiconductor production may be used in a fission detector design. Since it is closely related to the technique used for high uranium density fuel development, it is possible to perform their testing at a research facility with no fissile material; the boron simulates neutron absorption in uranium-235. A small neutron source will be used to predict neutron flux distribution, critical mass, etc. The analysis takes into consideration several aspects of the high energy density nuclear fuel design including the assumptions that, in electrodynamics, the vector potential is proportional to the scalar potential and charges of one polarity are balanced at the surface by a vacuum field displacement current.

**KEYWORDS:** coupled fast-thermal reactor, depleted uranium, Lorentz theory.

## **1. Introduction**

At present, the nuclear power technology is based on an earlier military reactor model. It is mainly a pressurized or boiling light water reactor (LWR) in which electrical-in-nature nuclear energy is converted to thermal, then to mechanical and finally back to electrical energy. The huge plant size and complicated fuel management systems resulted in the high fuel and capital costs of the LWR. A typical fuel assembly remains in the LWR for 3 years to a burn-up of 30 GWd/t or less than 7% of the fuel assembly nuclear energy used. To achieve this burn-up, only fresh, low enriched uranium fuel or less than 1% the uranium ore energy content is used.

The loss of the large energy content and safety concerns justify needs in transmutation of the nuclear waste. Several nations have programs to use the fast reactor for waste transmutation. However, fast reactors have the high cost and extremely short prompt neutron lifetime. One recycling technology, used by a small number of nuclear power plants, is mixed oxide (MOX) fuel, a mixture of uranium oxide and recovered plutonium oxide. Since plutonium produces significantly fewer delayed neutrons than uranium, its use essentially compromises the safety of conventional reactors.

## 2. Breed and Burn Reactor Core Design

In the conventional reactors, an excessive amount of reactivity is designed into the reactor core at start-up so there will be sufficient reactivity to sustain core operation over a long period of time. Several steps must be taken at that time to properly control the present nuclear reactors. Also, the generation of gases upon the fission of the fissile fuel presents at least a two-fold problem: First, fission product gases such as xenon and krypton effectively reduce reactor efficiency. Second, fission product gases or other volatile products may be sufficient in amount to create excessive pressure to cause the fuel container to deform. However, their migration can be used to effectively remove gas fission products as well as to greatly increase the reliability of reactor control.

The proposed core is comprised of a small fast booster that serves mainly as a neutron multiplier and a large thermal blanket with mainly fertile fuel. Use of a heterogeneous or particulate fuel element permits transport of the delayed neutron and gamma emitters from the blanket into the booster, where they can provide additional neutrons (source-based mode) or all the necessary excitation without an external neutron source (self-regulating mode). Then the gaseous fission products would be stored as solid products in the well-protected hydrogen production facilities outside the core. Axial power distribution could be regulated by a small neutron source [1].

This concept is based on the coupled fast-thermal reactor idea first presented by Avery to increase the prompt neutron lifetime in a fast reactor. According to Avery, the coupled two-zone reactor kinetics is determined by four integral parameters. There are  $k_{11}$ ,  $k_{22}$ , the multiplication factors of the zones 1 and 2 on their own;  $k_{21}$  and  $k_{12}$  are the coupling coefficients [2]. Another way to provide the one-way coupling plays on the relative geometrical arrangement of the two regions [3].

If we consider  $k_{21}$  as a parameter, it can be shown for the stationary state that the overall gain of the system is approximately equal to  $A/(1-Ak_{21})$ , where  $A = k_{12}/(1-k_{11})(1-k_{22})$  is the gain of the system with  $k_{21}=0$ . Since feedback and external neutron sources are only changing the neutron flux and power level, the proposed design with  $k_{22}$  is not greater than 0.95 and  $k_{11}$  is not greater than 0.98 is always sub-critical. Since the most prompt neutrons produced in the blanket cannot penetrate into the booster, the feedback value is mainly due to delayed-neutron emitter circulation. The main effect of the circulation on reactivity is in the increasing role of delayed neutrons.

Monte Carlo calculations with MCNPX code have partially tested the model. Preliminary analysis showed that a fuel assembly formed from the vented fuel elements could have a relatively high power density and a very long life. Each fuel element made of fissile fuel micro-spheres and a porous matrix with depleted uranium granules has several gas-flow channels. The gas could be carbon dioxide, helium or argon. The rectangular or cylindrical fuel element may also be in the form of a metallic matrix with embedded fissionable particles or fibers. Also, a particulate or liquid fuel can be used.

Although the thermal neutrons are mainly captured in fissile fuel micro-spheres, most of the fission fragments are escaping into the matrix or gas flow channels. When the matrix is dissolved, the fission products can be removed. The specific ionization losses in the low Z gas are much greater than the ones in the high Z fuel. Thus a small thickness of gas is sufficient to extract enough of the energy of the fission fragments.

For example, by using carbon dioxide at a pressure of 40 bars, with a flow velocity at the fuel assembly exit being 50 M/s, a power density of about  $300\text{MW/m}^3$  could be obtained. Then gas can be used to raise the steam temperature. A self-powered gas circulator can also be used as a heat removal system if the primary system is out of order. Water removes 70% of the thermal energy or about 500MW from the reactor core and the gas coolant removes the rest of the heat. Gas flows first downward through the blanket and then upward through the booster, exiting the core through the central port. Because the reactor has a negative temperature coefficient, its power distribution can be maintained by controlling the gaseous flow rate and moderator density.

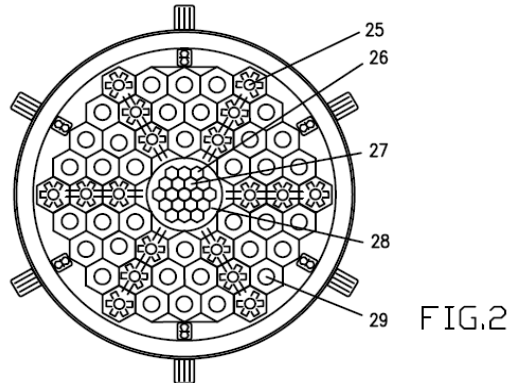
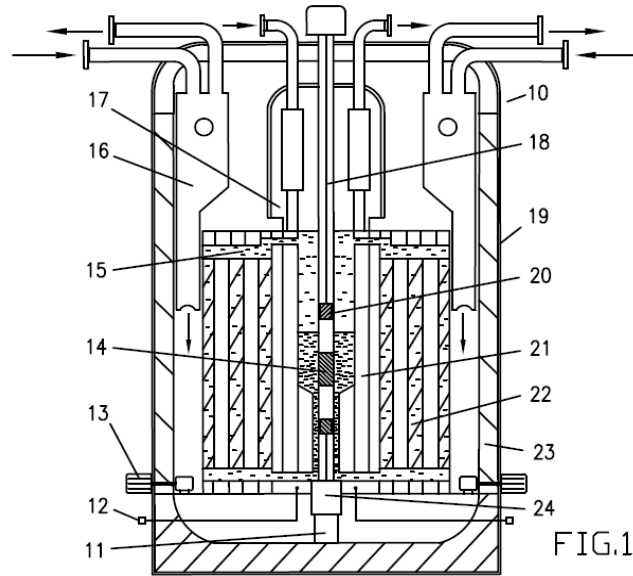


FIG. 1 and 2. Integral breed-burn reactor cross sections.

The reactor vessel 19 houses the booster 21 with enriched fuel 14 and gas fission product filters 27 made of depleted uranium and minor actinides, compact heat exchangers 16, feedback loops 15 and inner reflector 28. The blanket 22 with mainly depleted fuel 29 has a radial arrangement of the vented fuel assemblies 25.

### 3. Vented Fuel Element Design

In most reactors, the fuel assemblies include a plurality of fuel rods and hollow guide tubes that provide channels for neutron absorber rods or start-up neutron sources. Also, an instrumentation tube is located in the center of some assemblies. A disadvantage of the traditional nuclear fuel rods is the limited heat exchange surface area per unit volume that limits the power density. In the vented fuel assemblies, each pin consists of an inner tube and an outer tube, encircling the fuel matrix with a plurality of small channels through which the secondary coolant and fission products can flow.

In FIG. 3A and 3B, cross-sections of the heterogeneous and pellet annular fuel elements that could fit into the VVER or LWR-type fuel assemblies are shown. The cylindrical fuel layer is on the order of 2.4 mm in thickness, and it contains many more gas and fuel layers than are shown in the drawings. In the in-core superheating mode, the annular fuel element is cooled internally by steam and externally by boiling water [4].

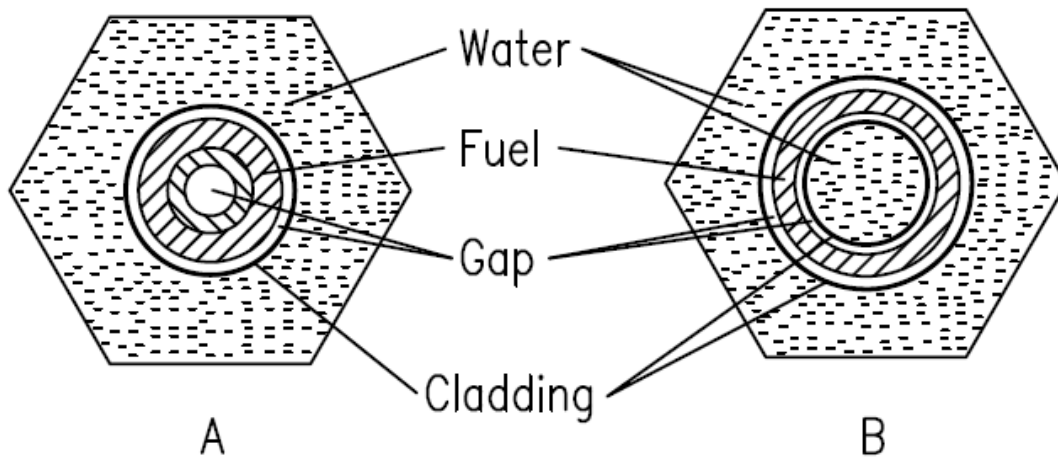


Figure 3. Schematic of annular fuel elements.

To increase surface area in direct contact with gas flow, during manufacturing process the flow channels will be incorporated according to the desired path of gas flow in pellet-type fuel. Gas flows through fuel pellets and then it is directed to a booster. If fuel temperatures are higher than  $775^{\circ}\text{C}$ , gaseous and volatile fission products will be essentially removed from the blanket fuel elements.

Although intended for the gas-cooled heavy-water reactor designs, the technology can also be used in other types of nuclear reactors. In the mid 1980s, in-core monitoring systems that included some aspects of this design were tested at research and power reactors. Each of the instrumentation tubes housed 5 gamma-sensitive calorimetric detectors. The signal conversion factor and power distribution were computed every 20 seconds from the previous values by using a simple recurrent formula.

These experiments demonstrated that uses of semiconductor properties of actinide could lead to essential improvement of reactor performance. Uranium dioxide is an insulator below about 775<sup>0</sup> K, but it becomes an excellent n-type (sub-stoichiometric) or p-type (hyper-stoichiometric) semiconductor as increasing temperature or suitable radiation promotes electrons across the band gap of about 1.3eV.

### 3.1 In-core fission detector

At least one fuel element in each modified LWR fuel assembly is arranged as a vertical cathode in parallel orientation to a suitable anode to form a fission detector. Both uranium oxide and boron carbide could be employed as detector materials. The difficulties of accurately measuring neutron fluxes, especially in a start-up mode, will be overcome by the use of optical or electrical processes originated in the detector medium. In operation, incident radiation creates ions, electrons and holes, which cause an accumulation of charge on the electrodes according to the spatial distribution of power.

Read-out means are provided to output a signal, representative of the accumulated charge. The neutron detector development could open doors for the design of multi-layer fission voltaic fuel. Each layer could include a pair of Schottky or p-n diodes made of depleted uranium or thorium separated by a thin layer of enriched fuel. At operating temperature some metal could combine with oxygen and form sub-stoichiometric dioxide. A voltage-dependent depletion region is adjacent to the central layer.

The open-circuit potential of the diode that includes electronegative and electropositive semiconductors is equal to the difference between the work functions of its anode and cathode. Therefore perfection necessary for a p-n junction does not apply to the cell with a built-in potential. Electron-hole separation and reduction of recombination may be enhanced at least in part by a dielectric effect and a magnetic field produced by the flow of current through the electrodes. By combining radiation-assisted thermal effects in the fuel material having semi-conductive characteristics, several forms of energy conversion are integrated to develop a power source in which the efficiency of each method could be added.

The fuel elements could be formed from a cylindrical or hexagonal matrix with a central passage containing a collector cooled by fluid such as water. The central emitter could be constructed of tungsten and thorium oxide. Also, porous tubes with gas-cooled fissile fuel are placed at the corners of the matrix. The fuel can be in any of a variety of ways, such as by forming annular pellets or by pouring particulate fuel into a casing member. The cooling fluid maintains the collector at a much lower temperature than the emitter that results in the generation of current. Also, certain fission fragments such as noble gases, bromide and cesium can migrate from the hot fuel through the central port.

Both the cladding and port tubes connected electrically only via an external load are able to carry a current in excess of hundred amperes. When determining the load resistance, the maximum efficiency for any electric power source occurs when the internal resistance of the power source is the same as the load resistance. Since gas cooling requires high pressures and large circulating volumes, a liquid coolant is preferable with a weapon-grade plutonium fuel. Gallium is a candidate for use as the cooling and direct energy conversion medium because in the liquid state it is a semimetal.

#### 4. Model-based Nuclear Fuel Test Facility

The proposed control system will rely on two forms of the same application: hardware means and a physical model that calculates the reactor parameters by dividing the core into a plurality of cells. Since the neutron flux in any cell is independent of whether it is produced by a large number of neutron sources simultaneously (as in the reactor) or by a single source placed in each cell, an inexpensive test facility could be used to handle all operations not involving high radioactivity.

The facility consists of a water-filled tank containing several tubes that are coated with boron-doped depleted uranium to form a core. In this approach, the fuel element simulators with a neutron absorber have the same configuration as the reactor's fuel. Small neutron source and fission detectors, which are an integral part of the fuel element prototype, will be used to predict neutron flux distribution, critical mass, etc. The results of earlier measurements with a Po-B neutron source for up to 18g boron carbide per channel, equivalent to 324g  $U^{235}$  are presented in [5].

The possibility of applying this method to other fuels is connected with finding a suitable neutron absorber able to simulate the properties of the fuel. For example, the capture cross section of erbium has a resonance at thermal neutron energy such that it can be used to simulate plutonium. A fundamental problem in reactor safety is how to design a reactor with the least amount of fuel. The condition for this is a constant thermal neutron flux that could be studied in the facility.

The detailed designs of a new fuel or in-core sensor must be preceded by expensive experimental work. However, to work with fissile materials, one will need to obtain the necessary licenses. At this time, it is almost impossible. This is why we are going to use the fuel test facility, which involves neither fissile material nor high neutron fluxes. The facility could also play an important role in predicting the performance of semi-conductive electronic devices at high radiation levels. Two methods for the cost-effective enhancement of conversion properties of fission detectors will be analyzed. The first involves depleted uranium particles coated with fissile fuel in a porous matrix. The second is fuel formed from layers of uranium dioxide or carbide, with each layer having different stoichiometry or atomic arrangement [6].

Recently, researchers at Massachusetts Institute of Technology performed a comprehensive study of the tube-in-duct and annular fuel concepts. Their results allow the power density of a conventional reactor to be raised by 50% within current safety limits. However, to reach a real breakthrough, recent advances in dispersion nuclear fuel technology will be applied to the LWR fuel design. In addition to having long operational lives, these fuel elements are expected to have a high conversion ratio.

After the development of vented fuel assembly prototypes and analysis of their conversion and thermal properties at the test facility, irradiation testing will be performed at the research reactors. To the extent possible, the hardware developed in earlier studies of the high uranium density fuel will be modified in order to measure the properties of the fuel samples such as a voltage-current, capacitance-voltage curve and total currents at relevant heat fluxes. The dynamics of the reactor could be analyzed at the existing coupled critical fast and sub-critical thermal modules.

## 5. Breed and Burn Reactor Fuel Development

At present, the only commercially available option for recycling the actinides such as plutonium and perhaps neptunium is a reactor partly fueled with mixed oxide fuel. Recently, a new dispersion fuel element having high uranium density fuel in a zirconium matrix filled with standard  $\text{PuO}_2$  powder has been proposed. As compared to MOX fuel, the new fuel has higher thermal conductivity and fuel density. Its advantages are a simple production process that is easily realized remotely; feasibility of plutonium and minor actinide transmutation with the more environmentally friendly fuel cycle [7].

Novel dispersion fuel elements (see FIG. 3A) could allow advanced water reactors to achieve a high conversion ratio. The fuel element with zirconium and depleted uranium alloys can be fabricated by the capillary infiltration method. Under the action of capillary forces, the molten zirconium alloy provides a metallurgical bond between fertile fuel and cladding and protects it from interaction with fission products. Pores of the matrix contain micro-spheres of fissile material. Also, researchers at Purdue University employed a polymer infiltration and pyrolysis method to enhance the thermal conductivity of LWR fuels [8].

Since the reactor is sub-critical and has a conversion factor of about one, its fuel burn-up is mainly limited by radiation damage rather than criticality. The proposed fuel cycle consists of two parts: 1) the simple dry processing with or without cladding replacement; 2) after total exposure for about 400GWd/t, the fuel assemblies will be removed from the reactor and sent to a reprocessing facility. Both aqueous and pyrochemical methods can be applied for the fuel reprocessing. The fuel recycling will include stages that are traditionally considered in a closed fuel cycle with separation into three streams: U+Pu+Np, Am+Cm+Rare Earths and remaining fission products. The cost of reprocessing would be comparable to the enrichment cost, about \$250 per kilogram of uranium. The fuel cycle without uranium enrichment process is proliferation resistant due to the low concentration of fissile material in all process steps.

There are alternative reprocessing methods such as a room temperature liquid ion, supercritical liquid carbon dioxide or halide (fluoride or chloride) volatility process. The last one is using difference in volatility of halides. In this process, uranium and plutonium are recovered by techniques such as distillation, partial condensation and adsorption. In this process, gaseous uranium, plutonium, and neptunium are separating from fission fragments and remaining actinides. As a result, high purity uranium, a mixture of uranium and plutonium and a fission product are recovered independently of one another.

Of the several dry processes, this separation works best in uranium based systems such as the breed and burn reactors. Also, the aqueous method used in processing of research reactor fuel is considered as a joint process for the spent fuel reprocessing and radioisotope production. Fuel pins could have thin, uniform or corrugated cylindrical cans comprised of a bonded uranium dioxide matrix and the ports permitting access to the interior of the pins. In several thin film layering steps, the layers can be deposited directly onto the tube surfaces. Alternatively, they can be deposited on a separate substrate. The thickness of the each deposit can be up to 50 milligrams per square centimeter. The electrolytic baths could employ an aqueous solution containing uranyl compounds that can be enriched in the fissionable isotope and chemical additives.

The process can also be employed to deposit uranium onto metals of other shapes. For example, double-sided flat plates can be plated with uranium oxide. Furthermore, instead of being in the form of a flat layer, the stack of plates can be wound to form a spiral or circular or other cross-section. The inner and the outer cans are made from materials such as stainless steel, nickel, zirconium, zircaloy, aluminum or carbon fiber. The latter was chosen because of high radiation resistance of graphite materials. In the course of developing the in-core fission sensors, there are needs to deposit thin uranium-oxide layers onto the inside or outside walls of hollow cylindrical cans. The simplest approach appears to be electro-deposition techniques recently used in scintillation-type in-core neutron sensor production [9].

Although uranium dioxide is chemically stable and inexpensive to manufacture, its low thermal conductivity limits the power upgrades. It is possible to increase its thermal conductivity by adding another material. Several techniques usually employed in semiconductor development can be used to the manufacture of the heterogeneous fuel elements. In some applications, a metal-organic actinide semiconductor such as uranium phthalocyanine and a solid proton conductor such as a hydrogen uranyl phosphate may be used.

## **6. Results and Discussions**

Preliminary studies have been performed on the depleted uranium and actinide recycling in a LWR-type breed-burn reactor. The reactor advantages are high specific power, high fuel burn-up, inherent safety, ease of control and simple fuel handling. In addition, it has high breeding potential, low delayed neutron loss, direct energy conversion capability, and low construction material cost. A significant advantage of the design is that the fuel may be used in the reactor core as long as it's required to reach a target fuel burn-up, limited by radiation damage rather than criticality.

At the beginning, a spent fuel is used to produce fissile material. Then enough fissile material is produced to sustain the chain reaction in the core for a long time. The development of new nuclear power reactors requires a careful analysis of the nuclear safety of the reactor and the reliability of heat removal from the core. Small fuel particle size leads to overlapping plasma zones. The use of plasma as a high-temperature conductor permits increase of thermal and energy conversion efficiency of the dispersion fuel. The proposed design would greatly reduce operational safety concerns. Important requirements for this are exclusion of the possibility of attaining a critical state and use of fuel with a low content of fission products and fissile isotopes.

Through the studies, several experimental methods will be used to model fission product buildup, fission gas removal, and thermal and electrical properties of the proposed fuel. The charge produced in a fuel medium by the charged particle is proportional to the energy loss or the stopping power at the specific distance of penetration. When a fission fragment penetrates the device the electric field is reconfigured as the mobile electron-hole pairs created by its track cancel out the electric field originally contained in the depleted region. The field funneling effect was experimentally observed in silicon surface barrier detectors. An electric field is set up at the end of its track such that the total potential drop remains constant.

This electric field defines the spatial extent of the funnel and is highly time dependent. As time progresses after the penetration by the ion, the field retreats back to the original configuration. Charge is therefore collected by the total field, which extends to the end of the track outside the depletion region. The plasma charge generated along an ion track is fully collected even when the depletion width is less than the ion range.

A strong electrical current flow in the electrodes creates a magnetic field directed at right angles to the heat flow in the fuel. This, by the Nernst Effect, produces a radial electric field gradient and electric charge displacement within the fuel medium. A counterpart Maxwell charge displacement in the vacuum field medium could form a surface charge of one polarity at the cladding. From the solution of Maxwell equations it can be shown that the sum of these currents is independent of position, and charges of one polarity are balanced at the surface of finite thickness by a vacuum field displacement current in a reference frame in which the magnetic field is absent.

Historically, a long time before quantum mechanics, Lorentz suggested that some disturbances, like waves, could be transmitted with traveling particles through a certain medium without moving it. At that time, instead of careful analysis of the systematic errors in the Michelson experiments, some scientists chose to postulate constancy of light velocity. Mathematically, it was based on the Lorentz transformation that preserved a wave equation in a moving reference system. Since it equally applies to any wave motion, the anisotropic values for the velocity of light or sound had to be used in all calculations, including Einstein's original manuscript.

The Lorentz theory, therefore, is still a useful working tool to analyze the observed phenomena. It is shown that the Klein-Gordon metric satisfies so-called non-propagating waves. The electromagnetic forces are obtained as a description of these wave motions. This approach leads to the natural introduction of the field values (group velocity and intensity of de Broglie waves) into Maxwell's equations. The consequence of this approach is similar to the dielectric structure-based accelerator concept. The relativistic electron energy losses tend to the finite value in the non-magnetic medium and there are small transverse wake fields in the vacuum channel [10].

## **7. Conclusion**

The commercial nuclear reactor fuels were mainly developed before the revolutionary developments in semiconductor, composite material and nano technologies that have occurred over the past few decades. The development of photovoltaic technology is now at the heart of the clean energy initiative. However, this goal is not complete without nuclear waste recycling. To address this need, it is crucial to develop a high performance nuclear fuel.

The implementation of this fuel into nuclear power technology could potentially save billions of dollars annually by burning nuclear waste efficiently, while at the same time greatly reducing our dependence on fossil fuels. Conversion of the deep geological repositories into underground electricity and fuel production facilities does not need a large investment nor transportation of highly radioactive material, and could greatly simplify the nuclear infrastructure. Countries without an established uranium enrichment infrastructure can also implement the fuel cycle.

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